Chapter 8
Fire Safety and Fire Resistance of Building Structures and Timber Constructions

Abstract This chapter presents general approaches to the system of fire safety in buildings and thermal fire regime's assessment. Dynamics of change of fire hazard factors during fire growth is considered. Charring rate of timber species and glued laminated timber at nominal fire exposure is discussed. Fire resistance of timber building members and charring depth are presented.

Timber is widely used in Russian construction industry practice as a construction material for buildings and structures for various purposes. In the house-building industry, it is used as a construction material for residential, public, industrial, agricultural, livestock, warehouse, and other buildings and structures. In transport infrastructure, it is used as a railroad construction material (used as rail ties) and suspension bridge interchanges; in structures of water facilities, it is used to build small wooden bridges.

In cold northern and northeastern regions of the country with abundant forest resources, log buildings and structures (mainly in small towns and in the countryside) are still popular. Round timber log or machined flat ones are used. Development of the modern timber house-building industry is moving toward creating new progressive industrial technologies for manufacturing various structural materials made of natural timber (Romanenkov and Zigern-Korn 1984; Kovalchuk 2005). In particular, they include massive large-sized glued laminated timber (glulam), laminated veneer lumber (LVL), or cross-laminated timber (CLT).

In Russia, production of the above-mentioned glulam constructions began in the second half of the twentieth century.

Twenty-five plants using imported equipment with total capacity of about $100 \cdot 10^3$ m^3 of constructions per year had been operating since 1973. By 1997, during perestroika (economic restructuring of the former USSR), this sub-sector almost ceased to exist. It was not until later that glulam production was revived. Today glulam is manufactured by 50 companies, but only two of them are large-scale manufacturers with overall production capacity of $(40–60) \cdot 10^3$ m^3 of constructions

R. Aseeva et al., *Fire Behavior and Fire Protection in Timber Buildings*,
Springer Series in Wood Science, DOI 10.1007/978-94-007-7460-5_8,

per year. By 2008, more than 600 various buildings and structures with long-span glulam load-bearing constructions had been designed and built (Vatin 2008).

It should be noted that commercial production of new structural glued timber composites with an aligned structure had been launched abroad earlier, for example, oriented strand board (OSB) or parallel strand lumber (PSL) and laminated strand lumber (LSL).

Glued timber constructions (GTC) production is developing very successfully in Europe, North America, and Japan. World output of load-bearing and load-separating GTC was about $4.5 \cdot 10^6\,m^3$ in 2003 and $\sim 5 \cdot 10^6\,m^3$ in 2004. During the next 5 years, annual GTC output increased by 31 %. A further 25 % increase was expected from 2009 to 2013 (Competitive environment 2011).

Up to 2005, Russia manufactured just 2 % of the world's GTC. However, the GTC manufacturing sector is growing rapidly. For example, from 1998 to 2003, GTC output increased ten times, from $7.4 \cdot 10^3\,m^3$ to $76 \cdot 10^3\,m^3$. In 2005, glulam output alone was $67.7 \cdot 10^3\,m^3$. Approximately half of this output was used on the domestic market. Total contracted capacity of Russian GTC manufacturers is currently $456 \cdot 10^3\,m^3$/year. In the medium term outlook GTC will still be mainly used for low-rise structures, including houses made of glulam (70 %), light frame constructions (6 %), and new roofing assemblies (12 %) (Competitive environment; Development prospects of the glued laminated wood market 2009).

Massive large-sized glulam constructions (columns, beams, arcs, frames, trusses) are essential structural members of timber buildings and structures, and they can bear large operation loads. Other types of GTC (partition timbers, slabs, wall panels, etc.) include constructions performing enclosing function. All of these GTC provide stability and fire safety of construction facilities. These GT load-bearing and load-separating constructions are the subject of special attention, which is reflected in scientific, technical, regulatory, and guidance literature. The attractiveness of using GT constructions is due to their resistance to aggressive media, low bulk weight compared to metal and reinforced concrete, and considerable strength at low weight.

For example, glulam constructions were used in building facilities such as an indoor ice rink with a span of 58 m in Tver (Fig. 8.1); a mineral fertilizer warehouse in the port of St. Petersburg with a span of 63 m and a roof arch 45 m high (Fig. 8.2); the Bugry Trade Center with a span of 53 m in St. Petersburg; the Strogino ice rink with a span of 48 m in Moscow; a cable suspension bridge at the 102nd kilometer of the Moscow Ring Road (MKAD); and an aquapark in Mytischi, Moscow Region.

8.1 General Approaches to the Fire Safety System in Buildings and Assessment of Thermal Fire Regime

Timber buildings and structures have a very long service life, but they can be easily destroyed and burn out in a few minutes in case of fire. Fire may occur due to faulty wiring or careless handling of fire. As a result, materials and substances in the compartments initially ignite (temporary fire load) rather than timber constructions or cladding materials (constant fire load).

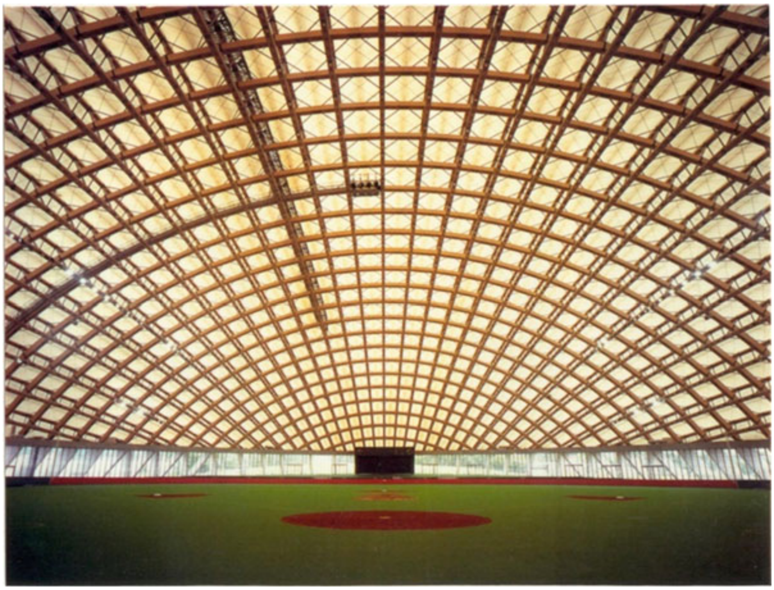

Fig. 8.1 Sports complex in Tver roofed with glulam bearing structures

Fig. 8.2 Structure of a mineral fertilizer warehouse in the port of St. Petersburg

Fire safety system at construction facilities is aimed at preventing the onset and development of fire, as well as preventing the impact of fire hazardous factors on people and preserving the stability of building and structures.

The concept of fire safety is complex and includes all necessary measures during the design, construction, and use of buildings and structures to ensure human life and health and minimize material losses in case of fire.

The concept of fire hazard factors includes all manifestations of fire that affect the state of people in a fire zone: direct effects of flame or sparks, high ambient temperature, reduced oxygen concentration and visibility in smoke, increased concentration of toxic products of combustion and thermal decomposition of materials, mechanical damage of structures, and other factors.

The main provisions of technical regulations on fire safety and general fire safety requirements for buildings and structures are given in Federal Law of the Russian Federation No. 123-FL dated July 22, 2008 (Federal Law of RF No. 123-FL). Some amendments were added later (Federal Law of RF No. 117). In 2011, a set of codes for design and calculation of residential, public, industrial, and other timber structures was enacted especially for buildings and structures made of solid timber and GT constructions (SP 64.13330.2011).

Design and calculation methods for GTC and solid timber structures and regulated and calculated values of the strength of timber constructions under various types of loading are also included in the standard (STO 36554501-002-2006).

Buildings and structures of all types are classified according to their degree of fire resistance and structural and functional fire hazard classes.

Buildings are divided into fire-resistance class I, II, III, IV, or V by their degree of fire resistance. The degree of fire resistance of buildings and structures is set depending on the number of floors (height of a building), floor area (fire compartment), functional purpose of the building (functional fire hazard class), and type of constructions used. One-story timber structures built of massive timber log may be assigned to fire-resistance class IV. Light timber frame buildings and structures with no special fire protection are assigned to class V.

The structural fire hazard class of buildings and structures depends on the same factors as fire resistance. All buildings and structures are divided into four classes according to structural fire hazard: C0, C1, C2, and C3. There are no special requirements for fire resistance and structural fire hazard class for timber housing up to two stories, inclusive. For three-story buildings, structural fire hazard class should not be lower than C2. Four-story residential buildings should have at least class III fire resistance and structural fire hazard class of the buildings no lower than C1.

Functional fire hazard classes of buildings and constructions are set depending on the purpose of buildings, the number of permanent or temporary occupants, and their age and physical state.

Constructions of any type are divided into four fire hazard classes: K0 – non-hazard; K1 – low hazard; K2 – moderate hazard; and K3 – high fire hazard. Timber constructions without fire protection belong to class K3.

A standard method is used to determine the fire hazard class of building constructions (GOST 30403-96 1996). The required structural fire hazard class for constructions is in accordance with the required structural fire hazard class for buildings and structures (Table 8.1) (Federal Law of RF No. 123-FL).

Table 8.1 Correspondence of the structural fire hazard class of buildings and structures to fire hazard classes of building constructions used

Structural fire hazard class of buildings	Fire hazard class of constructions				
	Load-bearing members (columns, girders, trusses)	External walls	Walls, partitions, floors, roofs, ceilings	Stairwell walls and fire barriers	Stair marches, landing (stairwell)
C0	K0	K0	K0	K0	K0
C1	K1	K2	K1	K0	K0
C2	K3	K3	K2	K1	K1
C3	Not regulated	Not regulated	Not regulated	K1	K3

The actual structural fire hazard class of buildings depends on the actual fire hazard classes of main load-bearing and load-separating constructions: columns, beams, trusses, walls, partitions, floors, roofs, walls, stairwells, flights, and stairwell landings. Class C0 buildings and structures have the best fire safety, as all constructions are made of noncombustible materials. The majority of class C3 buildings and structures (except for structural members of stairways, walls, stairwells, and fire barriers) have no fire safety requirements.

The degree of fire resistance of buildings and structures according to fire safety codes is regulated with consideration of the functional purpose of the buildings, number of floors, area, and other factors (Table 8.2) (Federal Law of RF No. 123-FL; SP 2.13130.2009). If the actual fire resistance limit (time to failure) of main building constructions is equal to or greater than the code value required, it is considered that the actual fire resistance of the building meets the requirement.

The behavior of building constructions during a fire depends on the temperature and duration of the fire. In turn, the type and amount of combustible substances and materials (fire load), their location in the room, room dimensions and configuration, sizes of openings in enclosures, and other factors affect fire temperature regime.

This means that with the same fire load, different variants of fire development are possible and each variant will correspond to a certain temperature – time fire regime.

In order to classify constructions according to fire resistance, standard fire regime is used, where the change in average volume temperature of the heating medium at the fire development stage is described by the following equation:

$$t = 345 \lg (8\tau + 1) + T_0, °\mathrm{C},$$

where τ – fire duration, min, and T_0 – initial temperature, 20 °C.

In actual conditions, fire temperature can be more “rigid” than the standard fire temperature (Fig. 8.3, curve 2). In this case, the fire resistance of a structure will be less than during a standard fire.

In a “softer” mode (Fig. 8.3, curve 3), fire resistance of a construction would exceed the value obtained during a standard test (Roitman et al. 2013).

Table 8.2 Correspondence of the degree of fire resistance of building and structures to fire resistance limits of building constructions

Degree of fire resistance of the building	Building constructions fire resistance limit, min						
				Non-attic roofs		Stairwells	
	Load-bearing wall, column, etc.	External non-bearing walls	Floor/ceiling assemblies (including attic and overbasements)	Decks (including insulation)	Trusses, beams, joists	Inner walls	Stairwell flights and landings
I	R 120	E 30	REI 60	RE 30	R 30	REI 120	R 60
II	R 90	E 15	REI 45	RE 15	R 15	REI 90	R 60
III	R 45	E 15	REI 45	RE 15	R 15	REI 60	R 45
IV	R 15	E 15	REI 15	RE 15	R 15	REI 45	R 15
V	Not regulated						

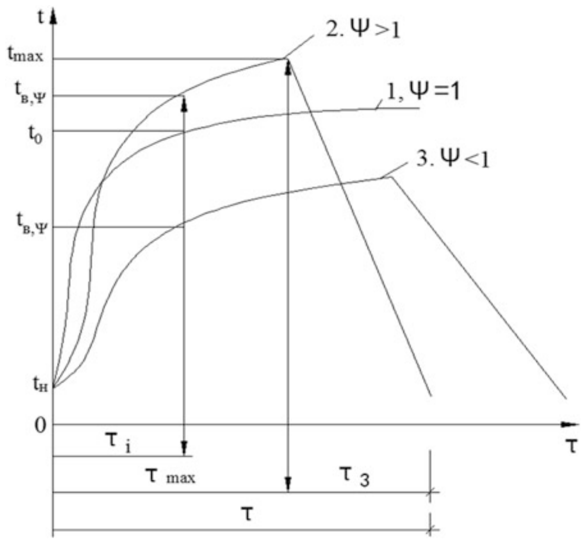

Fig. 8.3 Fire temperature regime: *1* standard regime, *2* more rigid than standard regime, *3* softer than standard regime

Temperature regimes of real fires at the development step are described by the following equation:

$$T = \psi\ 345\ \lg(8\tau + 1) + T_0$$

This equation differs from the previous equation by the presence of fire temperature coefficient ψ. The value of ψ is the ratio of temperatures of actual and standard fires at the same moments of fire development. The value of ψ can be determined by taking into account the opening factor K_{op} in the place of fire:

$$\psi = 1.37 - \left(150\ K_{op} - 0.65\right) / {K_{op}}^2 10^4,$$

where A_{op} – area of vertical openings, m^2; H – average height of openings, m; A – total area of all horizontal and vertical enclosures constructions in the room, m^2; and $K_{op} = A_{op}\sqrt{H/A}$.

For conditions that differ from standard fire conditions (Fig. 8.3), time τ_{max} can be calculated by the following formula:

$$\tau_{max} = \frac{Q_{CY}}{\left(8,318\ K_{op} - 4,021\ {K_{op}}^2\right)},$$

where Q_{CY} – value of reduced fire load (specific fire load, reduced to the total surface area of enclosures), MJ/m^2.

Then the value of the maximum temperature of a gaseous medium during an actual fire will be:

$$T_{max} = \psi\ 345\ \lg(8\tau_{max} + 1) + T_0.$$

The rate of temperature decrease at the fire extinction stage, °C/min, is equal to $V_{ext} = (98{,}000C_0 - 1{,}500)/Q_{CY}$.

A comparable approach that takes into account the area of openings and enclosures and the heat-absorbing capacity of enclosures is recommended when calculating parametric temperature–time fire dependence by European fire standard EN 1991-2-2002, which received the status of National Standard of Russia in 2011 (National Standard of the Russian Federation EN 1991-1-2-2011).

The time to reach the maximum temperature of a gaseous medium in the place of fire depends on the rate of fire development and its nature, i.e., whether it is controlled by the fire load or ventilation. Thus, the temperature regime in the place of fire depends on these factors at the fire extinction stage (National Standard of the Russian Federation EN 1991-1-2-2011).

Other methods for evaluating fire temperature regimes have recently been proposed. They include zoned and/or field modeling of gaseous medium behavior during a fire in a building (Astapenko et al. 1988).

8.2 Dynamics of Change of Fire Hazard Factors During the Fire Growth

Research of the initial stage of fire development inside the buildings and structures is important for organizing and safely evacuating people from these buildings. Determination of the time required to evacuate people from a burning building is based on knowledge of the dynamics of change of fire hazard factors (FHF) in a building with a specific functional purpose and with certain space-planning structure, taking into account the regularities of people's flow movement, human behavior, and the characteristics of the occupants (Holshchevnikov et al. 2009).

According to the valid standard (GOST 12.1.004-91 1992), the time required for safe evacuation is determined in accordance with critical fire duration until at least one fire hazard factor reaches the value that is critical for people:

$$\tau_{cr} = \min\left\{\tau_{cr}^{LV}, \tau_{cr}^{T}, \tau_{cr}^{tg}, \tau_{cr}^{O2}\right\},$$

where τ_{cr}^{LV}, τ_{cr}^{T}, τ_{cr}^{tg}, τ_{cr}^{O2}, $\tau_{cr}^{T\Pi}$ are values of critical fire duration in terms of loss of visibility, gas medium temperature, discharge of toxic combustion products, and oxygen concentration.

In fact, τ_{cr} is a complex index reflecting time up to appearance of critical situation for people in a compartment during a fire.

A rather detailed and comprehensive theory of FHF growth during the initial stage of fire in building is represented in the works (Koshmarov and Rubtsov 1999; Koshmarov 2000). A modified integrated model of pre-flashover fire in a compartment subdivided into zones is considered.

Work zone occupied by people is studied.

A mathematical description of the processes of the growing average volume value of temperature and other fire hazard factors indoors is expressed as a system of ordinary differential equations. These equations reflecting the laws of conservation and thermodynamics, together with boundary and initial conditions, form a closed system for determining fire characteristics in a closed space. Analysis of the full system of equations with some assumptions resulted in formulas for engineering calculation of the dynamics of the increment of FHF indoors.

In case of linear flame spread on the surface of materials, critical fire duration in terms of reaching critical temperature in occupied space is calculated with the following formula:

$$\tau_{\text{cr}}{}^{\text{T}} = \left[\left(\frac{B}{A}\right) \ln\left(\frac{T_{\text{cr}}}{T_0}\right)\right]^{1/2},$$

where complex $B = c_{\text{p}}\rho_0 T_0 V/(1-\varphi)\eta Q_{\text{L}}$; complex $A = 1/2 b_{\text{g}} v_{\text{fs}} \psi_{\text{sp}}$; T_{cr} – critical temperature for a person in the occupied space, equal to 70 °C; and T_0 – initial temperature in the compartment where the seat of fire is situated.

Dimensional complex B depends on combustion efficiency η and combustion heat of the material Q_{L}; index of heat loss to enclosure φ; free volume of the compartment V, and initial thermal and physical characteristics of the air environment in this compartment.

Complex A makes allowance for specific mass loss rate $\psi_{\text{уд}}$ and area of flame propagation (speed v_{fs}). In case of circular flame spread on the surface of a material, this complex can be represented by the following formula:

$$A = \frac{\pi\ v_{\text{fs}}{}^2\ \psi_{\text{sp}}}{3} = 1.05 v_{\text{fs}}{}^2 \psi_{\text{sp}}$$

In terms of loss of visibility:

$$\tau_{\text{cr}}{}^{\text{LV}} = \left\{\left(\frac{B}{A}\right) \ln\left[\frac{B\ D_{\text{m}}}{(B\ D_{\text{m}} - \mu_{\text{cr}})}\right]\right\}^{1/n},$$

where D_{m} – smoke generating ability of the material, Np m^2/kg^1; μ_{cr} – critical value of smoke optical density connected with the visibility range in a smoke-filled environment, $\mu_{\text{cr}} = 0.119$ Np/m^1; and $n = 3$ for circular flame spread on the surface of the material, and $n = 2$ for linear flame spread.

In terms of oxygen deficiency indoors:

$$\tau_{\text{cr}}{}^{\text{O2}} = \left[\left(\frac{B}{A}\right) \ln\left\{\frac{(B\eta L_1 + \rho_{01} V)}{(B\eta L_1 + \rho_{1\text{cr}} V)}\right\}\right]^{1/n},$$

where L_1 – specific oxygen consumption rate; ρ_{01} and $\rho_{1\text{cr}}$ – initial and critical values of average partial density of oxygen; and $\rho_{1\text{кр}}$ depends on the height of the occupied space. It is accepted that $\rho_{01} = 0.27$ kg/m^3 and $\rho_{01} - \rho_{1\text{cr}} = 0.0044$ kg/m^3; $n = 2$ (or 3) depending on the type of flame spread on the surface of the material.

Critical fire duration in terms of hazardous emission of each toxic combustion product:

$$\tau_{cr}{}^{tg} = \left[\left(\frac{B}{A}\right)\ln\left\{1 - \left(\frac{VX_{cr}{}^{tg}}{B\eta L_{tg}}\right)\right\}^{-1}\right]^{1/n},$$

where $X_{cr}{}^{tg}$ – maximum allowable amount of toxic agent indoors and L_{tg} – yield of combustion product emitted after burning of one unit of mass of material, kg/kg.

If a number is negative under the natural logarithm, the factor under study is not considered hazardous for this particular fire situation.

During calculation of fire hazardous factors, the following accepted maximum allowable limits for people are used: $T_{cr} = 343$ K; $X_{cr}{}^{CO_2} = 0.11$ kg/m^3; $X_{cr}{}^{CO} = 1.16 \times 10^{-3}$ kg/m^3; $\rho_{1cr} = 0.226$ kg/m^3; and $\mu_{cr} = 2.38/l_{LV} = 0.119$ Np/m^1 with l_{LV} – maximum allowable visibility range in a smoke-filled area, which is equal to 20 m.

Today, due to the development of computing technologies and implementation of powerful computers in engineering, not only integral and zone models of heat and mass transfer during fire but also more complex two- and three-dimensional field models are in demand in the area of fire safety (Puzach 2003). Computational field modeling makes it possible to solve complex problems of evaluating the dynamics of FHF into structures with complex configuration, taking into account the operation of all smoke exhaust and fire-extinguishing systems, to determine fire resistance of structures, etc.

We were interested in a simple problem – how the species of timber influences the dynamics of fire hazardous factors during the initial fire phase. Therefore, using a typical compartment with dimensions of $20 \times 10 \times 3.3$ m with small opening as an example, we evaluated critical fire duration by FHF at circular flame spread on the surface of timber panels as wall lining. During fire simulation, we considered timber panels made of coniferous and deciduous species: fir, pine, birch, and oak. Baseline data for calculating the time of onset of a dangerous situation for people during fire were obtained beforehand through the use of standard fire engineering methods (see Part 1). Circular flame spread is used as the most frequent type of flame propagation on a timber wall surface.

According to the results of our calculations, the most hazardous fire factor during fire simulation is generation of carbon monoxide.

Within a minute after the onset of fire in the compartment, the concentration of this toxic agent becomes critical. Furthermore, due to the lower rate of flame spread on the surface and mass burnout rate, deciduous timber species have a lower rate of increasing FHF. Critical fire duration calculated in terms of reaching dangerous concentrations of carbon monoxide in the compartment has the following sequence:

$$\begin{array}{rl} & \text{fir} < \text{pine} < \text{birch} < \text{oak} \\ \tau_{cr}{}^{CO}, \text{s}: & 52 < 57 < 61 < 72. \end{array}$$

8.3 Charring Rate of Timber Species and Glued Laminated Timber at Standard Fire Exposure

The question of charring rate of timber, glulam, and other types of timber-based products during a fire holds a central position in the studies of fire resistance of timber buildings and structures. This is only logical, because the fire resistance limit of constructions is determined by taking into account total time from the start of fire exposure of a timber structural member to the onset of charring and the time from onset of charring to reaching the limiting critical state.

Charring rate depends on the heat and fire exposure regime. Part 1 describes the effect of constant radiation heat flow density on the thickness of the surface char layer formed during flaming combustion of various timber species.

In this section, we examine the data on the charring rate of timber structural members in standard fire regime.

R. White and E. Nordheim performed a detailed study of charring of eight timber specimens of coniferous and deciduous species in standard fire regime (White and Nordheim 1992).

Using the regression analysis method, the following relationship between heat exposure time in fire conditions and charred layer thickness was found:

$$\tau = m{x_\mathrm{c}}^{1,23},$$

where τ – fire exposure time, min; x_c – the charred layer thickness, mm; and m – the correlation coefficient: the value inversely proportional to the charring rate. This index is a function of the apparent density of dry timber, ρ, kg/m^3; moisture content in the specimen, u, %; and charred layer shrinkage, f_c.

The charring rate index, m, is calculated by the formula:

$$m = 0.000564\rho + 1.21u + 0.532f_\mathrm{c} - 0.147, \quad \min/\mathrm{mm}^{1.23}$$

Here, f_c is a dimensionless parameter of charred layer thinning. It is defined as the ratio of charred layer thickness at the end of fire exposure to the initial thickness of the timber layer that could be charred. The authors (White and Nordheim 1992) believed that the f_c factor depends on the lignin content in the chemical composition of timber.

The value of the charring rate index for dry spruce wood with $\rho = 460$ kg/m^3 is $m = 0.47$ min/mm$^{1.23}$, whereas at 9 % moisture, $m = 0.58$ min/mm$^{1.23}$.

The charring rate for deciduous timber species in standard fire regime is 10–20 % lower compared to coniferous specimens.

The formula given above pertains to the test environment at standard temperature regime of timber constructions in no-load condition. It is known that mechanical stress applied to a specimen "helps" the thermal motion to destroy the material. But how does the loaded condition of a structural member affect the charring rate, if at all? This question remains unanswered.

Experience shows that the average charring rate of various timber species may vary from 0.6 to 1.1 mm/min and depends on many factors, in particular, on timber density (volume weight) and moisture, number of heated sides in the construction, heating duration, cross-section size, surface roughness, and others (Demekhin et al. 2003).

As timber density (volume weight), moisture, and cross-section size of a timber construction member increase, the average charring rate decreases. As the temperature of the heating medium during a fire, air intake, number of heated sides in the construction, and timber surface roughness increase, the charring rate of timber also increases. For example, at temperature–time standard fire exposure on four sides of timber columns in loaded condition, the charring rate increased 1.25–1.3 times compared to one-sided heating. With sufficiently long temperature exposure, the average charring rate of timber decreases.

The charring rate of solid timber is higher compared to glulam. In an experimental study of spruce beams with cross sections of 100 × 140 mm and 150 × 250 mm exposed to standard fire regime, the following average rates of charring propagating the from cross-section center were found (Zoufal and Kashpar 1986):

For solid timber beams:

Lateral charring rate was 0.65 mm/min.
Upward charring rate was 0.95 mm/min.

For glulam beams:

Lateral charring rate was 0.55 mm/min.
Upward charring rate was 0.85 mm/min.

It was also noted that the charring rate was not linear, and differed at various stages of timber combustion.

The charring rate of timber depends heavily on the type of load-bearing constructions and their service conditions (Gousev et al. 2008). In some European countries, there are standards establishing the average charring rate for various types of timber constructions at the design stage of building projects.

Thus, for example, circular letter N 91/61 of the Italian Ministry of Internal Affairs states the following average charring rates for various timber load-bearing construction types: external vault-forming beams and side beams – 0.8 mm/min; internal vault-forming beams – 1.1 mm/min; pilasters and columns – 0.7 mm/min; and other horizontal structural members – 1.1 mm/min. The Italian National Standard “Analytical fire resistance assessment of timber structural elements” that was published later specified charring rates of 0.9 mm/min for solid timber and 0.7 mm/min for multilayer glulam.

Tests of various unprotected timber construction members in standard fire regime show that the average charring rate is about 1 mm/min and ranges from a minimum value of 0.6 mm/min for dense and wet timber to 1.2 mm/min for light and dry timber (Gousev et al. 2008).

From the relationship between heat energy balance in the pyrolysis front and on the charred surface layer during timber combustion, the authors of work (Strakhov et al. 2000) obtained the analytic dependence of charred layer thickness buildup, δ_c, on time t adjusted for char shrinkage.

This was made possible through a series of assumptions: quasi-stationarity of the combustion process, relatively small pyrolysis zone thickness, predominantly radiation heat exchange between the flame and flammable material surface, and the use of a pre-specified temperature profile in the material being decomposed according to an exponential law. The shrinkage coefficient of the charred layer, β_{sh}, as well as the yield of carbonized residue, K, as a result of material pyrolysis, are assumed to be constant. The following equation was obtained:

$$\delta_c = \sqrt{2a_c t + b_c^2} - b_c$$

where b_c is a parameter that incorporates the thermal conductivity of the charred layer and radiation heat transfer from the flame at temperature T_f

$$b_c = \frac{\lambda_c}{A_{eff}\sigma T_f{}^3}$$

where $A_{eff} = 1/[(1/\varepsilon_f)\ (1/\varepsilon_w - 1) + 1/\varepsilon_w]$ is the effective function of radiation parameters of the flame and combustible surface and ε_f and ε_w are radiation capacities of the flame and combustible surface. Parameter $a_c = (1 - \beta_{sh})\lambda_c(T_f - T_c)/\rho[(1 - K)L_v + c_p(T_c – T_0)]$ incorporates the ratio of the heat transferred from the flame toward the pyrolysis front to the heat consumed for gasification of the combustible material.

For combustion of Douglas fir at $T_f = 1{,}200$ K and assumed timber properties: $\rho = 450$ kg/m^3, $c_p = 2{,}800$ J/kg·K, $k_c = 0.5$ W/m K, $\beta_{sh} = 0.2$, $K = 0.2$, $L_v = 1{,}820$ kJ/kg, and $T_c = 623$ K, the calculation showed that the charred layer thickness in 20 min of combustion reached almost 18.5 mm. The average charring rate was 0.925 mm/min. After the onset of pyrolysis in spruce timber, the mass rate of pyrolysis for this period decreased from 12 to 4 g/m^{2}s (Strakhov et al. 2000).

We have determined the average charring rate for coniferous and deciduous timber in standard fire conditions in a small-scale fire furnace with specimens sized $150 \times 150 \times 30$ mm heated on one side for 20 min. Under these conditions, the onset of active charring in the specimens is observed 4–5 min after the start of the test. Table 8.3 shows the average charring rate values obtained for timber and the characteristics of the surface char layer.

As can be seen from Table 8.3, the deciduous timber specimens charred at a lower rate compared to fir and pine. They form a thinner but denser surface char layer.

The lower thermal inertia value, $\lambda\rho c$, of deciduous species is probably due to the formation of a more homogeneous fine-porous char structure.

The charring rate of unprotected construction members in standard fire regime under one-dimensional heat transfer is usually assumed as the base value in the

Table 8.3 Charring parameters for various timber species and the properties of surface char layer

Specimen	δ_{char}, mm	β_0, mm/min	ρ_{char}, kg/m^3	$T_{s\ char}$, °C	$(\lambda\rho c)_{char}$, kJ^2/m^{4}K^{2}s
Fir	23	1.15	225	780	0.140
Pine	19	0.95	268	732	0.133
Birch	13.5	0.675	285	718	0.115
Oak	9.2	0.46	348	700	0.119

design of timber buildings and structures. For example, Eurocode 5, EN 1995-1-2 recommends a basic charring rate of 0.65 mm/min for coniferous specimens 20-mm thick with density of 450 kg/m^3. If the thickness and density are other, the basic charring rate is multiplied by the specified coefficients (EN 1995-1-2 2004).

If a timber construction is heated on three or four sides with allowance for edge curves, the recommended charring rate for coniferous species is $\beta_0 = 0.8$ mm/min, whereas for glulam and LVL, $\beta_0 = 0.7$ mm/min (EN 1995-1-2 2004). The domestic code (SP 64.13330.2011) recommends assuming a constant charring rate equal to 0.7 mm/min for coniferous timber construction members.

When structural fire protection is utilized, the European standard (EN 1995-1-2 2004) emphasizes the charring onset time in the protected structural member. The fire protection effect of a multilayer construction system in this case is considered additive: it consists of the sum of the fire protection action duration of each layer. The reciprocal influence of adjacent layers on heat transfer variation in complex load-bearing constructions and enclosures of timber structures is covered in the technical guideline of (Fire safety in timber buildings 2010). It was shown that when fire protection is available, the charring rate of a protected timber construction slows down. But after failure of the fire protection, charring proceeds at an accelerated rate that exceeds the charring rate of unprotected timber.

8.4 Fire Resistance of Timber Building Members and Charring Depth

In the construction of timber buildings and structures, two main structural systems with various functions of timber constructions being used can be specified. (1) Frameless structures of massive logs or beams with load-bearing and load-separating constructions for external walls. (These are so-called heavy timber buildings.) Walls take all vertical loads, as well as horizontal loads through the floor/ceiling assemblies of the building. (2) Frame buildings, where the main load is taken by the frame constructions. This type of building can be divided into structures with large-span massive load-bearing constructions and light frame timber buildings.

In a framework structural system, vertical load-bearing constructions are columns, and crossbars, beams, and trusses perform the function of horizontal load-bearing constructions.

Timber frames with massive bearing constructions are used in large-span public buildings (sports halls, exhibition halls), as well as one-story industrial buildings and agricultural enterprises. Frameworks in these buildings may be single-span or multi-span, with or without hanging tap-beams with a capacity of up to 3 tons designed for operating buildings and structures in a normal temperature regime and in corrosive environments.

Timber structures are used to build post-and-beam, frame, and arched frameworks. Post-and-beam frameworks are designed mainly for industrial buildings. Beams or trusses overlap spans with sizes from 6 to 8 m or from 12 to 30 m. Arches with ties are used in construction of large spans. Frames are designed for single-span public and industrial buildings with spans from 12 to 24 m. Bearing frames may be formed of rectilinear elements (crossbars, posts) connected by pegs or fingers. Curved frames can also be used. Arched frameworks are designed for single-span public and industrial buildings (chemical raw material and fertilizer warehouses, etc.) with spans up to 60 m or more. Arch height is usually at least 1/6 of the length of the span L, and the depth of the arch is up to $1/30L$.

Light frame timber buildings are designed for the low- and medium-rise residential sector, offices, small shopping centers, etc.

As the load-bearing timber constructions in frame buildings, glulam and LVL beams with constant and variable depth, metal–timber trusses, brace flatworks (arches, frames), and spatial structures in the form of vaulted and domed covers are used as the load-bearing timber constructions in frame buildings.

Coniferous species – pine and spruce, more rarely larch and cedar – are generally used to manufacture load-bearing timber constructions. Hardwood timber is used to make dowels, timber pads, and other parts.

One of the main requirements for timber constructions s with bearing and separating functions is to provide acceptable fire resistance.

Fire resistance of timber constructions depends not only on the type of material (glued or solid timber), but also on the presence of reinforcement elements, articulator connectors, dimensions and cross-sectional configurations of the structural member, values of mechanical loads, structural fire protection, fire exposure conditions, and many other factors.

The stability of timber constructions at fire and their ability to maintain their bearing and enclosing functions are characterized by a quantitative index – fire resistance limit in standard fire conditions.

Standard methods are used (GOST 30247.0-94 1996; GOST 30247.1-94 1996) to experimentally determine the fire resistance of timber constructions. Russian methods as per GOST 30247.0 and GOST 30247.1 are similar to the ISO 834 and ASTM E-119 standards for parameters of fire furnaces and time–temperature fire regime.

Standard temperature dependence on fire development time is described by the equation:

$$T_\mathrm{f} - T_0 = 345 \ \lg \ (8\tau + 1)\,,$$

where T_f and T_0 are the current and initial temperatures in the furnace chamber, °C, respectively, and τ is the time, min.

The fire resistance limit of timber constructions may be determined by calculation on the basis of patterns of charring rate and heating of their cross sections at standard fire exposure.

When designing timber structures, it is important to ensure that the fire resistance limit of timber constructions with the connection elements and supporting nodes, including metallic and nonmetallic reinforcement, is no lower than the required fire resistance limit for this assembly in general.

The main signs of the limit state of bearing structures and enclosures are:

1. Loss of load-bearing capacity (sign R) occurs due to the collapse of the structure or the appearance of limit deformations (e.g., abnormal bending).
2. Loss of integrity – through cracks or holes in constructions or joints (sign E), through which combustion products or flame get into an adjacent room.
3. Loss of thermal insulating capacity (sign I) – a temperature rise on the unexposed surface of the structure of more than to 160 °C or higher 180 °C on average at any point of the surface.
4. Achieving limit values of heat flux (3.5 kW/m^2) at a standardized distance (0.5 m) from the unexposed surface of the construction (sign W).

Fire resistance of a building construction is the actual fire resistance limit determined by the time of occurrence (in minutes) of one or more sequential standardized signs (R, E, or I).

The fire resistance limit of timber constructions is usually determined by the time in which cross-section load-bearing capacity decreases due to charring and initial heating to the actual load value.

It has been found experimentally that glulam has higher fire resistance than solid timber. This can be attributed to the better structure of the glued elements, as well as the use of heat-resistant adhesives in the glulam industry. Thus, a glued timber beam with cross section of 100×140 mm has a fire resistance rating of 35 min during tests, which is 10 min more than fire resistance rating of solid timber with a similar section (Zoufal and Kashpar 1986).

The most important factors determining fire resistance of timber structures are cross-section dimensions of the construction and the number of heated sides during fire exposure. The results of determining the fire resistance limit of timber beams as a function of cross-section size and heated sides at standard fire temperature regime are shown in Table 8.4.

The results presented in Table. 8.4 show that decreasing the size of the cross section significantly reduces fire resistance ratings. Therefore, a structure with

Table 8.4 The effect of heating conditions on the fire resistance limit of timber beams with various cross sections

No	Type of construction	Fire resistance limit, min
1.	Timber beams, bending stressed, unprotected (three-sided fire exposure) with dimensions in mm	
	100 × 140	25
	120 × 160	30
	140 × 200	40
	180 × 260	50
2.	Timber columns, unprotected, buckling stressed, with flexibility $\lambda = 75$ (four-sided fire exposure) with dimensions in mm	
	120 × 120	10
	160 × 160	15
	200 × 200	20

100 × 140-mm cross section has a fire resistance rating of 25 min, while a structure with 260-mm cross section has a rating of 50 min or twice as long. An increase in the number of heating side reduces the construction's fire resistance rating.

The cross-section configuration of timber structures has a strong influence on their fire resistance and fire safety. For example, in elements with a rectangular cross section, the corners are charred more intensely during "standard fire," and they start rounding 10–15 min after timber charring.

Ribs and similar protruding elements with a large ratio of heated surface area to heated material volume ignite faster than flat or convex elements with a large radius of curvature (Roitman et al. 2013).

In case of fire, the fire resistance of timber construction is determined mainly by the decrease in load-bearing capacity of their timber elements and joints of these elements.

The bearing capacity of timber structural elements is reduced by charring and reducing the size of the effective cross section able to take the actual load and because of the changes in strength of timber in the non-charred part of the section (Roitman et al. 2013). The change in the load-bearing capacity of nodal connections in a fire is affected both by timber charring and reduced strength of steel components used in timber constructions, i.e., steel dowels, reinforcement units – pads, etc. (Fig. 8.4).

The timber charring process is necessarily accompanied by a decrease in the timber structure's effective cross section. Due to its porous structure and low thermal conductivity, the char layer serves as a thermal barrier and restricts oxygen access to the non-charred cross section of a structure. Uneven temperature distribution over the cross section behind the charring front leads to uneven changes in mechanical and thermal properties of the timber at different points of the cross section.

Fig. 8.4 The collapse of wooden structures in a fire due to loss of strength of steel connections

The following formula can be used to calculate the average temperature in the middle section of a timber structure at standard fire temperature regime with allowance for charring rate and heating conditions:

$$T = (1 + kb/h)\ [20 + 180(\beta\tau_f)^{\eta}/\ (1-\eta)\ \ (b/h - \beta\tau_f)]\left\{(b/h)^{1-\eta} - (\beta\tau_f)^{1-\eta}\right\},$$

where b and h – the initial width and height of the cross section of a timber structural element; β – the charring rate; τ_f – the duration of the fire; and k – coefficient accounting for the number of heated sides.

The value $k = 0$ is used for 2-sided heating, $k = 0.25$ for 3-sided heating, and $k = 0.4$ for 4-sided heating of construction. η parameter takes into account the duration of the fire: $\eta = 0.398{\tau_f}^{0.62}$.

The temperature is distributed from the charring front with a temperature of 300 °C toward the center section of massive glued timber elements according to a hyperbolic law. Mechanical properties of timber vary linearly with temperature in certain heating intervals.

Mechanical stress applied to a timber sample increases destruction of the material. Thus, the fire resistance limit of 3 m pine beams with a cross section of 120 × 410 mm decreased from 65 min to about 20 min as the load in the middle of the beam increased from 2,300 to 9,200 kg at standard fire temperature regime (Haritonov and Hmelidze 1989).

It should be noted that under the same mechanical loading conditions, larch beams showed a fire resistance limit nearly 25 % higher than the pine beams. The charring rate of larch timber beams and charred layer thickness were also lower.

According to (Janssens 2004), a similar effect was observed during the testing of Douglas fir glulam with a cross section of 222×419 mm and length of 4.57 m by ASTM E 119 standard. The central part of beams 3.76-m long was exposed to fire in a furnace. Beam loads were evenly distributed at two points at equal distance, such that they were 27, 44, and 91 % of the design value. Permissible stress and stiffness values corresponded to 16.55 MPa and $E = 11$ GPa. Glulam failure under these conditions occurred after 147, 114, and 85 min, respectively. During this period, the charred layer thickness reached 81, 74.5, and 57.3 mm, respectively.

At standard fire temperature regime, the actual fire resistance limit of timber constructions, Π_{ac}, is determined by the sum of time from the start of thermal effect on the timber in a fire before charring, τ_0, and the time from the start of charring before the ultimate limit state in a fire, τ_{cr}:

$$\Pi_{ac} = \tau_0 + \tau_{cr}, \text{min}\,.$$

The latter value is determined from the timber charring rate:

$$\tau_{cr} = \frac{(\delta_{cr} - \delta)}{\beta},$$

where β – the charring rate, mm/min; δ_{cr} – charred layer thickness at the ultimate limit state, mm; and δ – thickness of the wood behind the charring front, which has zero strength.

In a recent edition of the updated set of codes for timber structures (SP 64.13330.2011), it was recommended to take the thickness of this layer equal to 7 mm, as in Eurocode 5 (EN 1995-1-2 2004). Thus, it is assumed that a timber layer heated from 175 to 300 °C should not be taken into account when calculating the fire resistance limit of timber structures, due to a significant reduction or loss of strength properties. The critical thickness of the charred layer, δ_{cr}, should not exceed 0.25 part of the smallest size (thickness) of the section.

The general principle of calculating fire resistance of building constructions in case of fire is to solve two problems: heat engineering and static (mechanic strength). The goal of the heat engineering task is to evaluate the temperature distribution over the cross section of timber constructions, its heating time, and time to reach the critical value. The purpose of the static task is to calculate the time to reach the ultimate limit state of a structural element by strength loss due to the change in mechanical properties as a function of temperature and the time to reach its critical value.

Exact calculation methods for fire resistance limit of building members, including solid timber and other composite materials, are based on mathematical modeling

and numerical solutions set partial equations of heat transfer and static using modern computers. In this case, input data are required to characterize heat construction materials, in particular, knowledge of the kinetic decomposition parameters and thermal and mechanical properties of timber in a wide temperature range. The presence of fire protection requires the corresponding data on the characteristics of the fire protection material (Strakhov et al. 2000; Koshmarov et al. 1990).

These calculations are very complex. Therefore, simplified methods and techniques for solving specific problems, in particular, finite difference methods and analytical solutions, are used in engineering practice.

Base values of the resistance solid coniferous timber and glued members to various stressed states (bending, compression, stretching, shearing, etc.) are listed in (SP 64.13330.2011; STO 36554501-002-2006).

To take into account operating, loading and dimensional changes, the layer thickness in glued structures, the presence of nodes and connections, and other factors, the appropriate coefficients are used.

The principle of applying the relevant coefficients to take into account the influence of different factors on the onset of charring (fire resistance) of bearing and enclosing elements of constructions is implemented in Eurocode 5 and technical guideline (EN 1995-1-2 2004; Fire safety in timber buildings 2010).

Timber members in light frame structures with no fire protection lose their load-bearing function in a fire within a few minutes. Adequate fire protection for all bearing constructions, correct sequence of flame retardant separating panels and insulating layers in the general assembly, and also fire protection of joints increase the fire resistance limit of light frame assembly to 120 min. The material of the first layer of protective membrane is of great importance. Plasterboard as first protective layer of timber structures contributes the most to increasing the fire resistance limit of the assembly. A positive contribution is also made by mineral insulation between the walls of constructions.

Despite the fact that structurally achievable fire resistance limit may be high, timber constructions remain fire hazardous. The fire hazard class of construction is determined as per GOST 30403-96 (1996). The fire hazard class of timber construction must be determined in order to establish the extent of their participation in the fire development and the occurrence of fire hazards. Fire hazard class depends on the fire safety of the materials from which constructions are made. Unprotected solid timber belongs to materials of class G4 (highly combustible), B3 (easily flammable), and D3 (high smoke generation capacity), and glulam with no fire protection is a material with fire safety indices G4, B2, and D3 (Koshmarov 2000).

In this regard, the use of timber constructions without proper fire protection is limited. It is especially limited in construction of large public and industrial buildings and structures. Modern methods of fire protection of timber structures can significantly reduce the risk of fire.

References

Astapenko VM, Koshmarov YA, Molchadskiy IS, Shevlyakov AN (1988) Thermogas dynamics of fires in room. Stroyizdat, Moscow, 448 p

Competitive environment (2011) http://киск-красноярск.рф

Demekhin VN, Mosalkov IL, Serkov BB et al (2003) Buildings, constructions and their stability in fire conditions. SFS Academy, Moscow, 656 p

Development prospects of the glued laminated wood market (2009) http://www.stroyinform.ru

EN 1995-1-2 (2004) Eurocode 5: design of timber structures, Part 1–2: general – structural fire design

Federal Law of RF No. 117 Amendments to Federal Law of RF No. 123-FL Technical regulations for fire safety requirements, dd. 10.07.2012

Federal Law of RF No. 123-FL Technical regulations for fire safety requirements, dd. 22.06.2008.

Fire safety in timber buildings. Technical guideline for Europe (2010) www.jrc.ec.europa.eu; ISBN 978-91-86319-60-1

GOST 12.1.004-91 Fire safety. General requirements. Moscow, 1992

GOST 30247.0-94 Building structures. Fire resistance test methods. General requirements. Standards Publishing, Moscow, 1996

GOST 30247.1-94. Fire resistance test methods. Bearing and enclosing structures. Standards Publishing, Moscow, 1996

GOST 30403-96 Building structures. Method of determining fire hazard. Moscow, 1996

Gousev AI, Paznikova SN, Kozhevnikova NS (2008) Enhancement of the fire resistance of timber constructions. Fire Explos Saf 15(3):30–35

Haritonov VG, Hmelidze TP (1989) The behavior of glued timber beams at standard fire conditions. Fire resistance of building components and fire safety people and property. Fire Safety Research Institute of Ministry of Internal Affairs of the USSR, Moscow

Holshchevnikov VV, Samoshin DA, Isaevich II (2009) Field studies of traffic. ASFS, Moscow, 191 p

Janssens ML (2004) Modeling of the thermal degradation of structural wood members exposed to fire. Fire Mater 28:199–207

Koshmarov YA (2000) Prognozing fire hazardous factors inside facilities. ASFS, Moscow, 120 p

Koshmarov YA, Rubtsov VV (1999) The process of growth of fire hazardous factors in industrial buildings. IFS, Moscow, 90 p

Koshmarov JA, Geraskov GV, Voinov AN, Molchadsky IS (1990) Mathematical modeling of charring during combustion of thermally thick material burning. FTHS, Moscow, pp 172–175

Kovalchuk LM (2005) Production of glued laminated wood structures, 3rd edn. RIF Stroymaterialy, Moscow, 336 p

National Standard of the Russian Federation EN 1991-1-2-2011, Eurocode 1: effects on structures – Part 1–2: main effects – effects on buildings in fire conditions. Moscow, 2011

Puzach SV (2003) Mathematical modeling of gas dynamics and heat and mass transmission in solving problems of fire-explosion safety. Academy of the State Firefighting Service of the Ministry of Emergency Situations of the Russian Federation, Moscow, 264 p

Roitman VM, Serkov BB, Shevkunenko YG, Sivenkov AB, Barinova EL, Pristupiuk DN (2013) Roitman VM (ed) Bulidings, structures and their fire-resistance, 2nd edn. ASFS, Moscow, 366 p

Romanenkov IG, Zigern-Korn VN (1984) Fire resistance of building structures made of effective materials. Stroyizdat, Moscow, 240 p

SP 2.13130.2009 Systems of fire protection. Providing fire resistance for protection objects. Moscow, 2009

SP 64.13330.2011 Wood constructions. Current edition. SNiP II-25-80. Moscow, 2011
STO 36554501-002-2006 Glued wood and all-wood construction. Moscow, 2006
Strakhov VL, Kroutov AM, Davydkin AM (2000) Koshmarov YA (ed) Fire protection of building constructions. TIMR, Moscow, 433 p
Vatin NI (2008) Long span bearing structures made of glued laminated wood. StroyProfil 1(63):38
White RH, Nordheim EV (1992) Charring rate of wood for ASTM E 119 exposure. Fire Technol 28(1):5–30
Zoufal R, Kashpar Y (1986) Study of timber constructions in terms of fire safety. Bulletin of the Specialized Higher School, Sofia, pp 70–88